TECHNICAL REPORT ARCCB-TR-92011

DYNAMIC STRAINS IN A 60-MM GUN TUBE - AN EXPERIMENTAL STUDY

T. E. SIMKINS
G. A. PFLEGL
E. G. STILSON

MARCH 1992

US ARMY ARMAMENT RESEARCH,
DEVELOPMENT AND ENGINEERING CENTER
CLOSE COMBAT ARMAMENTS CENTER
BENÉT LABORATORIES
WATERVLIET, N.Y. 12189-4050

DISCLAIMER

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

The use of trade name(s) and/or manufacturer(s) does not constitute an official indorsement or approval.

DESTRUCTION NOTICE

For classified documents, follow the procedures in DoD 5200.22-M, Industrial Security Manual, Section II-19 or DoD 5200.1-R, Information Security Program Regulation, Chapter IX.

For unclassified, limited documents, destroy by any method that will prevent disclosure of contents or reconstruction of the document.

For unclassified, unlimited documents, destroy when the report is no longer needed. Do not return it to the originator.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 1992	Final

4. TITLE AND SUBTITLE
DYNAMIC STRAINS IN A 60-MM GUN TUBE - AN EXPERIMENTAL STUDY

5. FUNDING NUMBERS
AMCMS: 643797C120012
PRON: 1A02ZNR2NMSC

6. AUTHOR(S)
T. E. Simkins, G. A. Pflegl, and E. G. Stilson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Benet Laboratories, SMCAR-CCB-TL
Watervliet, NY 12189-4050

8. PERFORMING ORGANIZATION REPORT NUMBER
ARCCB-TR-92011

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Close Combat Armaments Center
Picatinny Arsenal, NJ 07806-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Presented at the Sixth U.S. Army Symposium on Gun Dynamics, Tamiment, PA, 15-17 May 1990.
Published in Proceedings of the Conference.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

An exceptionally thin-walled gun tube was constructed to assess the applicability of steady-state deformations predicted by critical velocity theory. Strains created by internal pressure moving at subcritical, critical, and supercritical velocities were measured. Excellent agreement with steady-state predictions was observed throughout the entire subcritical regime. When the velocity of the moving pressure was only slightly greater than the critical value, a transitional state was noted. At higher velocities, the development of a trailing wave was observed and was found to be consistent with the theory. The existence of the predicted head wave was never actually observed. However, its presence was indicated in a frequency analysis of the data.

14. SUBJECT TERMS
Dynamics, Strains, Gun Tubes, Steady-State, Critical Velocity, Waves

15. NUMBER OF PAGES
21

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

DYNAMIC STRAINS IN A 60-MM GUN TUBE - AN EXPERIMENTAL STUDY

T.E. Simkins, G.A. Pflegl, and E.G. Stilson
U.S. Army Armament Research, Development, and Engineering Center
Close Combat Armaments Center
Benet Laboratories
Watervliet, NY 12189-4050

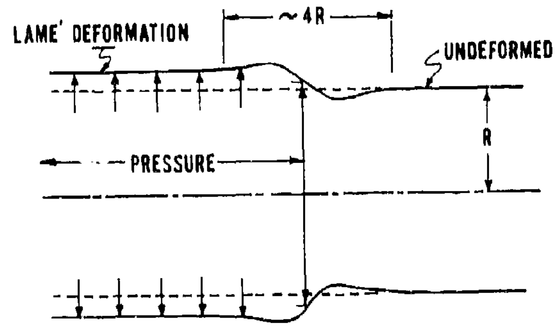
INTRODUCTION

The work reported herein was motivated by the need to further study the predictions of critical velocity theory as reported in July 1987 [1]. Whereas the circumferential strains reported in Reference 1 were in excellent agreement with those predicted by steady-state theory, questions remained as to the general applicability of the theory over a wider range of velocities. There was also great interest in the effects produced by small nonuniformities in wall thickness likely to be present in any production gun tube. With these goals in mind, funding was provided for a special set of experiments to be conducted in the Gun Dynamics Lab at Benet Laboratories.

BACKGROUND

A detailed account of the theory necessary to understand how wall strains amplify with projectile velocity is given in Reference 1. Reference 2 shows how bore eccentricity results in the excitation of nonaxisymmetric as well as axisymmetric tube strains, and Reference 3 discusses the manner in which transient vibrations produce even greater strain amplification. These references represent the state of our knowledge to date pertaining to critical velocity effects in gun tubes.

For the convenience of readers who are not acquainted with critical velocity theory and for the essential purposes of this paper, a brief summary is appropriate. **Figure 1** represents the general situation. The ballistic pressure, terminating at the obturation ring near the rear face of a projectile, travels along the bore surface of a gun tube. At low velocities, the deformation of the tube wall within the pressurized region of the tube is closely approximated by the Lamé [4] formula in regions sufficiently to the rear of the plane of obturation. The Lamé solution assumes a uniform tube of infinite length subjected to a uniform and statically applied internal pressure throughout. In most gun tubes, a distance of twice the bore radius to the rear of the plane of obturation is sufficient for the Lamé formula to apply, provided the projectile velocity is not too high. Similarly, at distances greater than twice the bore radius ahead of the obturation ring, the tube deformation is



DEFORMATION OF BORE SURFACE (STATIC)

Figure 1

almost zero. Closer to the obturation ring, however, the deformation is more accurately given by the solution of Laning and Bowie [5]. Like the Lamé solution, this solution also assumes a uniform tube of infinite length but under static internal pressurization which is applied over half of the tube only. The pressure is zero throughout the remaining half. This solution shows that the static deformation of the tube wall in the neighborhood of the obturation ring has the form of a decaying harmonic. At sufficiently low projectile velocities, this deformation exceeds the Lamé deformation by only a few percent and until now was disregarded in gun tubes. However, with the advent of higher projectile velocities for armor penetration and reductions in wall thickness to reduce weight, tube dynamics has assumed a dominant role and neither of these static solutions apply. Specifically, higher projectile velocities increase the amplitude of the harmonic portion of the deformation and decrease its wavelength until, at a specific 'critical' velocity, the amplitude theoretically grows without bound. The cause of this form of resonance is the equality of group and phase velocities at this particular wavelength. This only occurs at the stationary values of the phase velocity when expressed as a function of the wave number as described in Reference 1. The magnitude of this critical velocity decreases with the wall thickness of the tube (cf. Figure 13, Reference 1). The 'theory' referred to here assumes a uniform and infinitely long tube subjected to a moving 'step' of pressure travelling at constant velocity as depicted in Figure 1. The deformation is predicted from steady-state solutions. Admittedly, these solutions give no information about the transient development of this steady state. Figure 2 typifies the radial deformation at a fixed location along the tube for a projectile velocity close to critical, i.e., $V = 0.99 V_{cr}$* (t = 0 represents projectile passage). As can be seen, tube displacements (and hence strains and stresses) are approximately 3.7 times those calculated by the Lamé formula. Thus, the Lamé deformation, which errs only by a few percent when the velocity is, say 80 percent of its critical value, errs by 370 percent when the velocity is 99 percent critical. As $V \rightarrow V_{cr}$, this error theoretically becomes infinitely large.

*All plots of displacements are normalized with respect to those calculated by the Lamé equation.

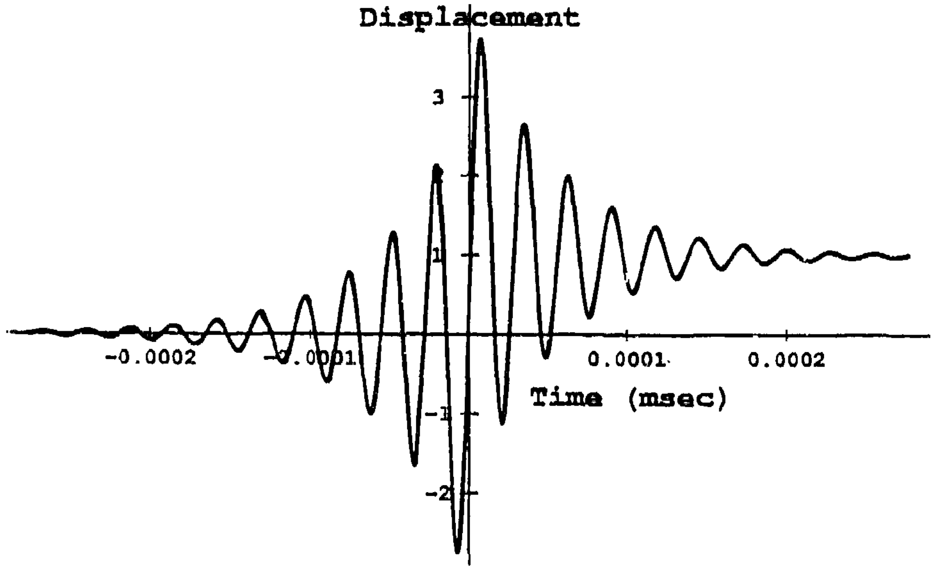


Figure 2. Theoretical steady-state radial displacement of tube wall, $V = 0.99\ V_{cr}$ (pressure front passes at $t = 0$).

Referring again to Figure 2, we see that the deformation is antisymmetric about the point (0,1/2) and has an exponential rise and fall. For velocities greater than critical however, the steady-state solutions have a completely different character. As shown in Figure 3 ($V = 1.22\ V_{cr}$), the steady-state deformation in the latter case consists of a trailing wave behind the obturation

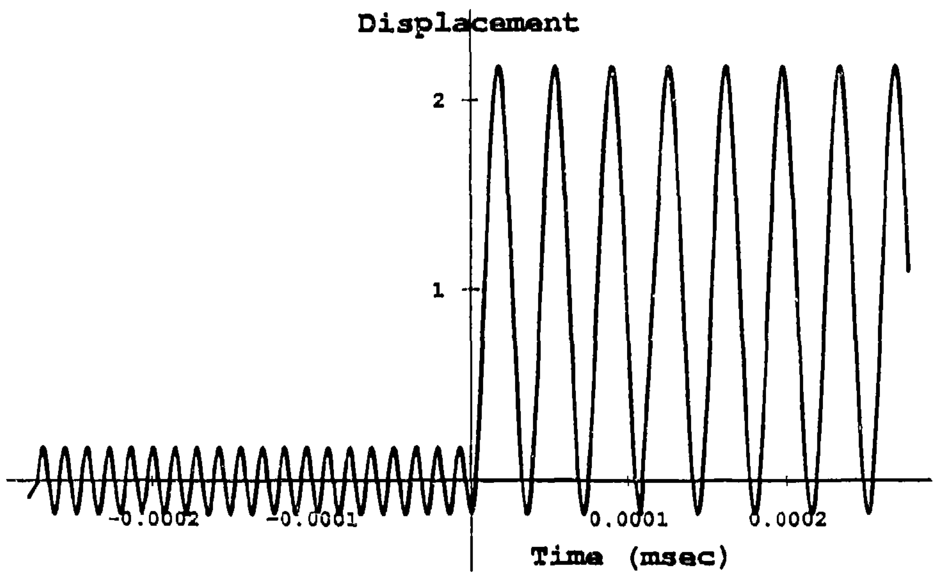


Figure 3. Theoretical steady-state radial displacement of tube wall, $V = 1.22\ V_{cr}$.

plane and a head wave in front. Both waves are predicted to have constant amplitudes and the amplitude and wavelength of the trailing wave are always greater than those of the head wave. Theoretically, as the velocity of the moving pressure becomes infinite, the amplitude of the trailing wave approaches twice the displacement predicted by the Lamé formula and that of the head wave vanishes.

As previously stated, the existing critical velocity theory yields only steady-state solutions for the tube deformation. In particular, it is not known how long it will take for a steady deformation to develop. While the strain data from the 120-mm XM25 [1] showed excellent agreement with the steady-state prediction, thus verifying the usefulness of the theory at subcritical projectile velocities, no strains were measured during these firings which test the usefulness of the steady-state solutions for supercritical velocities. Thus, one goal of the research reported herein was to compare measured values of strains obtained at supercritical velocities with those predicted by steady-state critical velocity theory.

NONAXISYMMETRIC DEFORMATION

In many practical situations involving mechanical vibrations, some coupling is often present which causes excitation of more than one mode of vibration. In particular, we are concerned about the possibility of exciting nonaxisymmetric (beamlike) waves in which the bore center line assumes a travelling sinusoidal shape. Motion of the bore center line at shot ejection suggests a time variant point of aim. As it turns out, there is good reason to believe that such a mode will appear in actual test firings because a beamlike mode exists which has a critical velocity extremely close to that of the axisymmetric mode. This is most easily seen by comparing the phase velocities of each mode as a function of wavelength (Figure 4). As described in Reference 1, phase and group velocities will be equal whenever these phase velocities are stationary. In particular, the axisymmetric mode and the nonaxisymmetric beamlike mode have minimum phase velocities which are practically identical. Hence the slightest coupling can be expected to transfer energy from the axisymmetric mode to the nonaxisymmetric mode whenever the projectile velocity nears this critical value. Nonuniform tube mass has been found to provide coupling by which this can occur [2]. A more comprehensive study of this effect and the effect of nonuniform wall thickness has been made at Rensselaer Polytechnic Institute [6]. Thus, a second goal of this research was to search for possible evidence of more than one mode of vibration, in particular, modes which represent a beamlike motion of the tube.

EXPERIMENTAL SETUP

Figure 5 depicts the 60-mm gun tube manufactured for these experiments. As the figure shows, the wall thickness of the tube is quite thick except over the last four feet approaching the muzzle - the test section within which all strain measurements are made. Within this region, the wall thickness is nominally a constant 0.120 inch. This thickness was as thin as manufacturing considerations

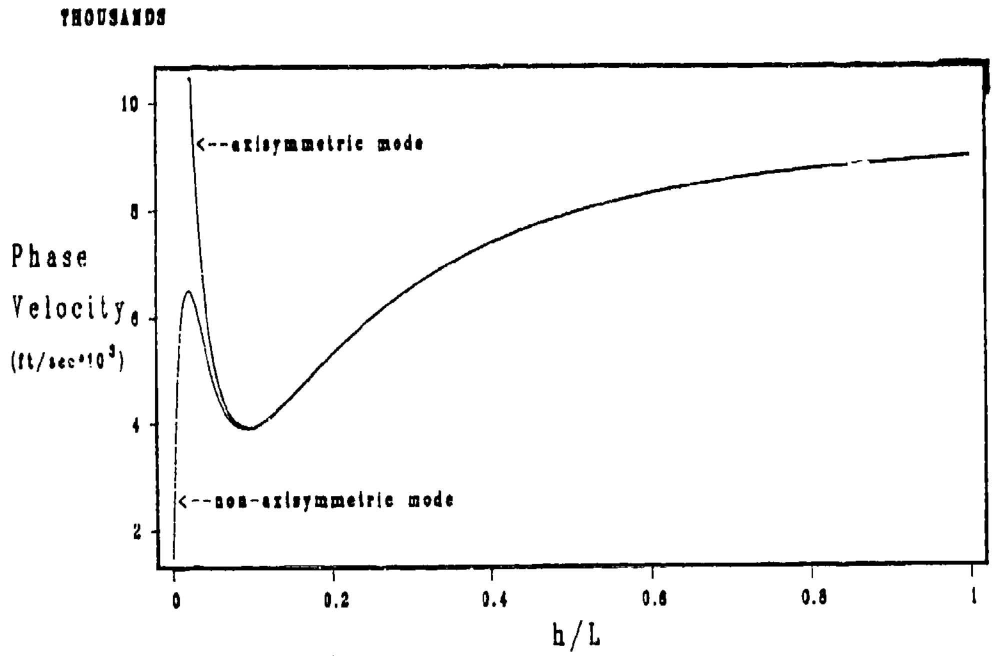


Figure 4. Dispersion curves for axisymmetric and nonaxisymmetric (beamlike) waves, h = tube wall thickness, L = wavelength.

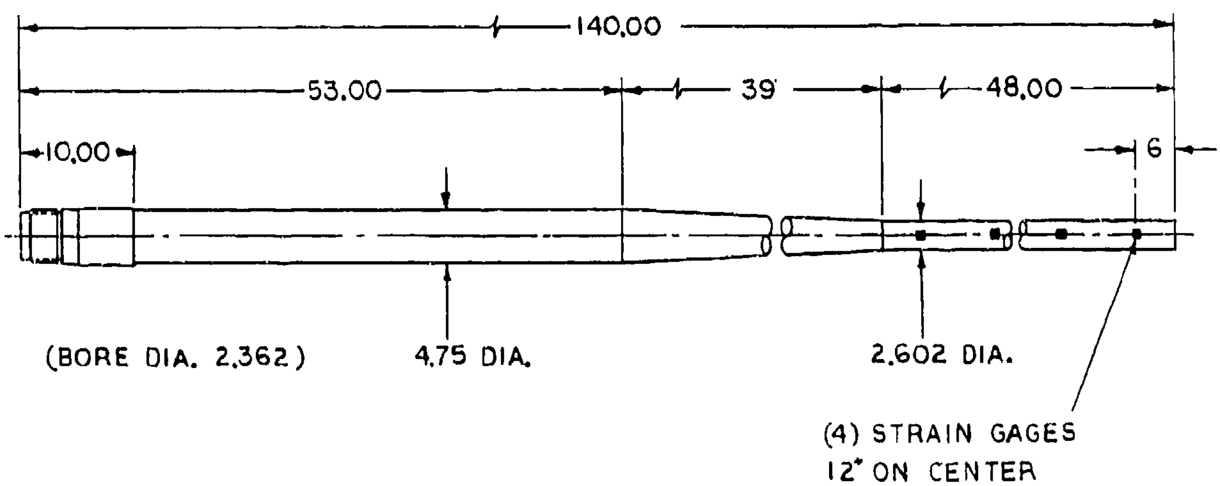


Figure 5. Schematic of 60-mm gun tube.

and structural integrity would permit to lower the critical velocity of the tube as much as possible. Using the thick-wall shell theory of Mirsky and Herrmann [7], the critical velocity for generating axisymmetric waves within this test section is 3924 ft/sec and that required to generate beamlike waves is 3917 ft/sec. The thin-wall theory (cf. Reismann [8]) gives a higher figure of 4089 ft/sec for the generation of axisymmetric waves. This theory does not include nonaxisymmetric deformation.

The gun tube is suspended by two pairs of steel cables, each approximately 0.25 inch in diameter. When fired, the tube recoils as a bar-pendulum--striking a buffer system only after shot ejection. This arrangement virtually eliminates vibrations from support reactions prior to the exit of the projectile. The buffer system consists of three hydraulic shock absorbers which make contact with a plate mounted concentrically on the rear surface of the breech cap. Figure 6 is a photograph of the entire setup.

In order to attain projectile velocities in the neighborhood of 4000 ft/sec, propellants normally used in sporting ammunition were used following the advice of Mr. J. Siewert of General Electric Company, Burlington, VT. The two propellants utilized were manufactured by E.I. duPont de Nemours & Company and are known as IMR 4350 and IMR 4227. The main difference in these two propellants is their rate of burn, the latter burning faster than the former. Both propellants have burn characteristics which are very sensitive to shot start pressure. If the chamber volume increases too early as a result of projectile movement, insufficient burning results. To ensure sufficient shot start pressure, the projectile was manufactured with a shoulder which constrains the projectile motion until it fractures and allows the body of the projectile to move forward. The thickness of the fracture surface was varied until satisfactory projectile velocities were attained. In all other respects, the projectile is simply a solid right circular cylinder of aluminum alloy (6061 T6). A photograph of the projectile appears in Figure 6.

Although the projectile is 60 mm in diameter, it is fired by a 30-mm cartridge preloaded with varying amounts of propellant, depending on the projectile velocity desired. The use of a 30-mm cartridge was simply one of convenience. Electrically actuated primers, flash tubes, and 30-mm Gau-8 cartridge cases were readily available and had already been approved by safety officials for use in previous experiments involving a 30-mm tube.

INSTRUMENTATION

Breech pressure, circumferential and axial strains along the outer surface of the test section, and projectile velocity were measured over the brief interval of time between ignition and shot ejection. Breech pressure was measured using a piezoelectric pressure transducer (Kistler Instruments, Inc., Amherst, NY). Strain gages were type EA-06-187BB-120 and were purchased from Measurements Group, Inc., Rayleigh, NC. Projectile velocity was measured using a radar interferometer model TROOK372A manufactured by RDL, Inc., Conshohocken, PA.

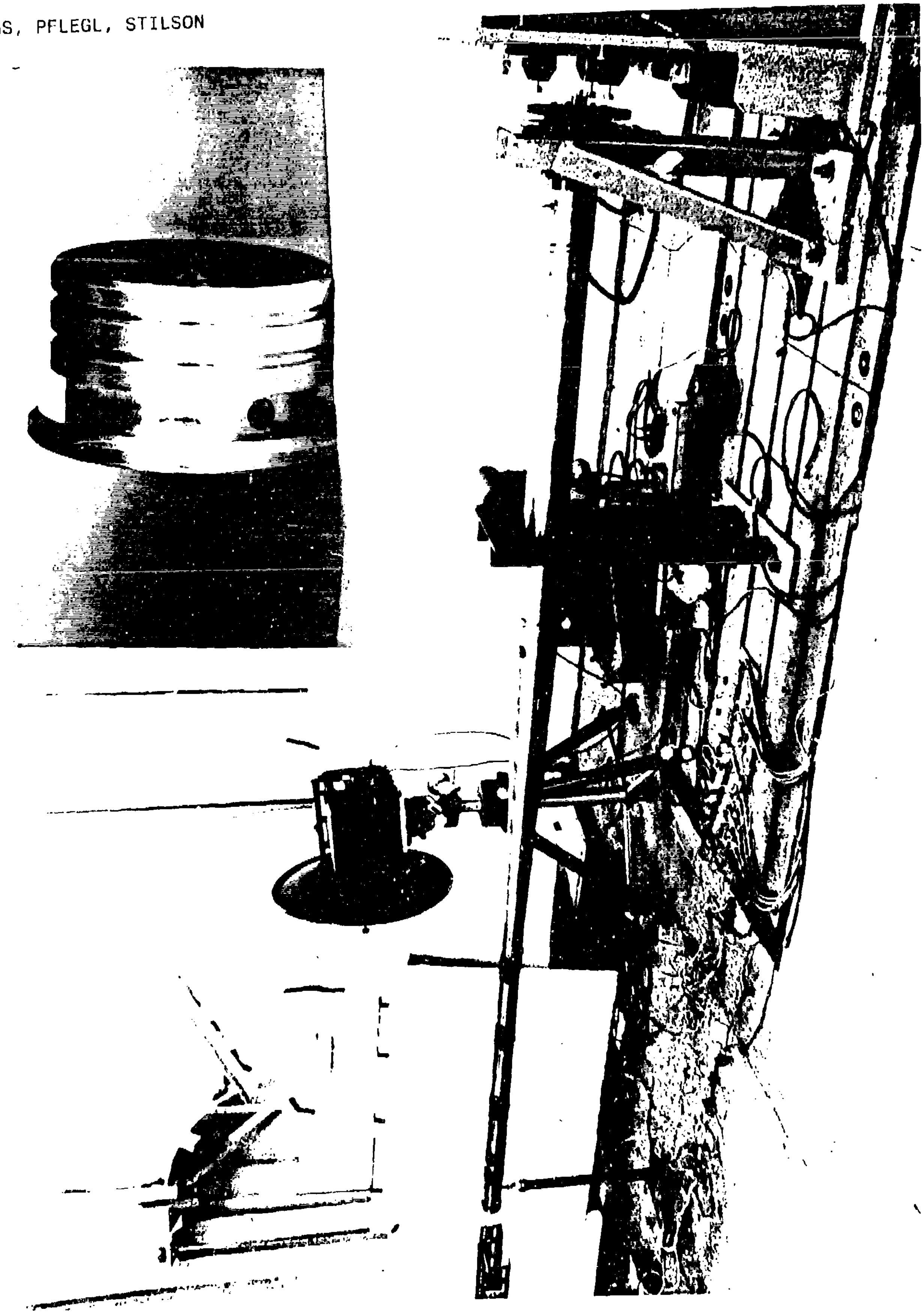


Figure 6. The laboratory gun tube and projectile.

The signals from the strain gages were received by model 8256 signal conditioning amplifiers (Pacific Instruments, Concord, CA). Output from these amplifiers and from the remainder of the transducers was received by model 9820 transient data recorders (Pacific Instruments) and also by three model 4094 Nicolet digital storage oscilloscopes. Some redundancy is provided between the Nicolet and Pacific systems. Digitized data from the Pacific system is stored on a hard disk with a tape backup and on floppy disks within the Nicolet oscilloscopes.

RESULTS

A typical set of measurements from one firing appears in Figures 7 through 10 (round ID 38). The plots were created using a computer program named VU-POINT: A Digital Data Processing System for IBM PC/XT/AT and Compatible Personal Computers, Version 1.21, March 1988. This software was purchased from S-CUBED, a division of Maxwell Laboratories, Inc., La Jolla, CA.

Figure 7 is a portion of a record of the Doppler radar output from which the projectile velocity can be calculated for any time. The radar signal has a frequency of 15 gHz which implies a wavelength of 1 cm. Thus, the time period of the oscillations is the time for the projectile to travel 1 cm.

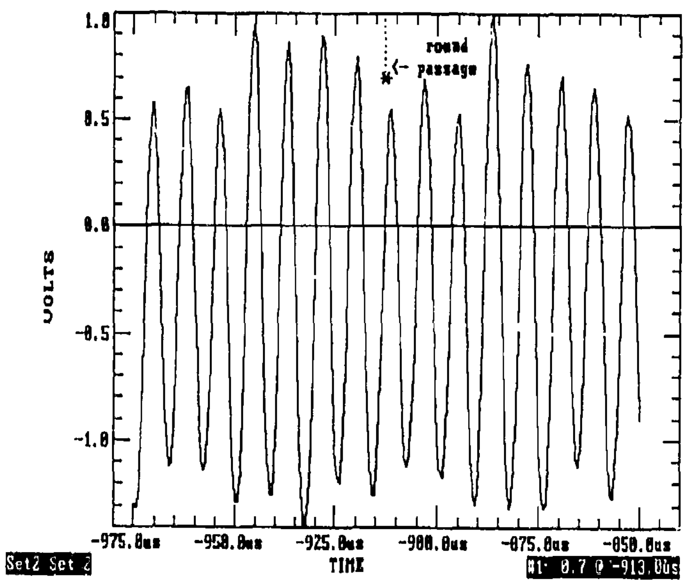


Figure 7. Doppler signal (round ID 38).

Figure 8 shows the pressure rise and fall at the initial location of the projectile in the breech end of the tube. The pressure acting on the rear face of the projectile as it traverses the bore is substantially less. In practice, the utility of the pressure measurement is marginal, serving mostly as a reference to compare burning characteristics from round to round.

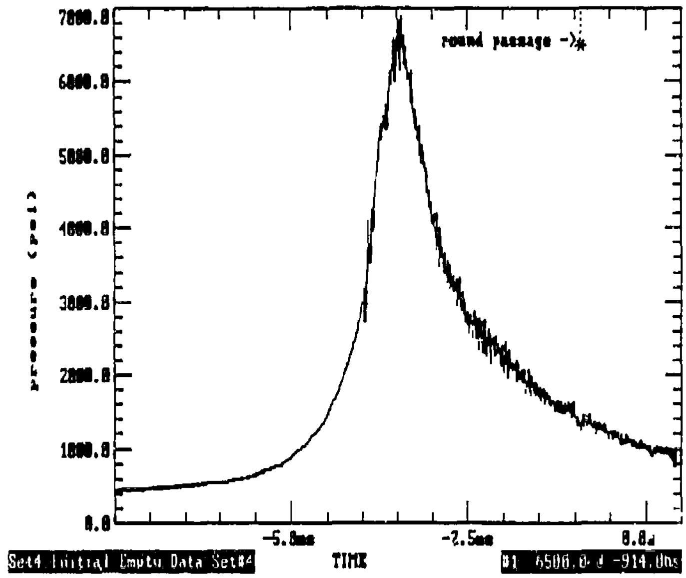


Figure 8. Breech pressure as a function of time (round ID 38).

Figure 9 shows the circumferential strain on the top surface of the gun tube located 30 inches from the muzzle. From the record, the time at which the projectile passes the gage is estimated to be t = -914 μs. (Times are measured from the time an electrical circuit is interrupted by the projectile at a location 12 inches from the muzzle.) Approximately 250 μs later (t = -663 μs), the projectile passes a similarly oriented gage located 18 inches from the muzzle. The record from this gage is shown in Figure 10. The time that the projectile passes each of these gages is shown in Figures 7 through 10.

A DETAILED ANALYSIS OF THE STRAIN RECORD OF FIGURE 9

The first signal to arrive is an axial strain created by the sudden recoil of the tube. This strain is mostly confined to the first axial mode of the tube and travels at the longitudinal wave speed of the tube material--roughly 17,000 ft/sec. The strain gage, mounted in the circumferential direction, senses the Poisson contribution from this strain, i.e., 30 percent of the axial strain appears as circumferential strain. The axial strain wave is practically constant in amplitude throughout the period of interest and can be subtracted from the record if desired. In any case, the axial strain is not of real interest in these studies.

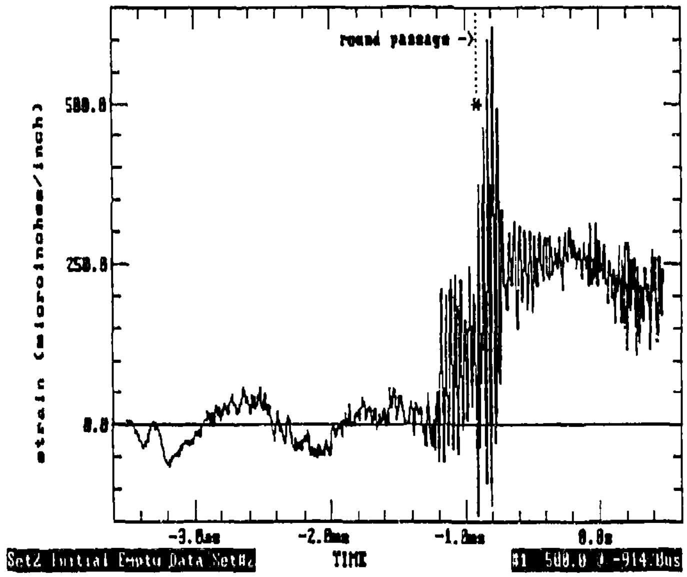


Figure 9. Circumferential strain 30 inches from muzzle. projectile velocity = 3905 ft/sec (round ID 38).

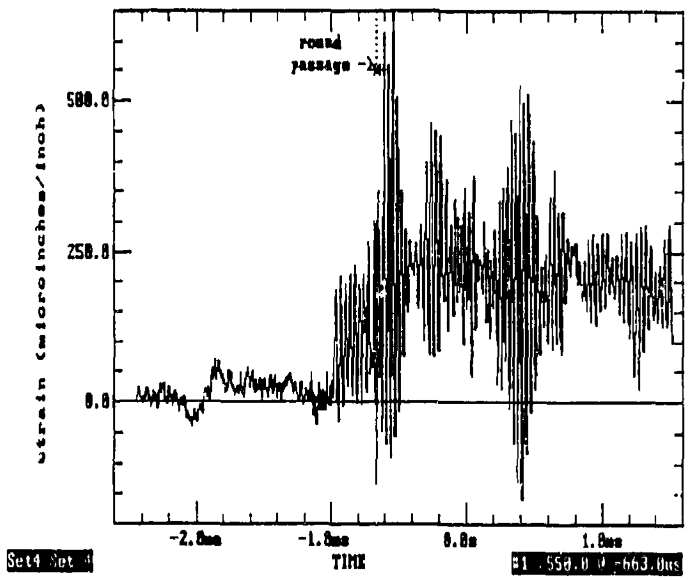


Figure 10. Circumferential strain 18 inches from muzzle (round ID 38).

Figure 11 is a time expansion of Figure 9 in the neighborhood of the time of shot passage (t = -914 μs). From the Doppler record, the projectile velocity is 3905 ft/sec (0.99 V_{cr}) and therefore subcritical. Consequently, one expects to see a strain similar to the theoretical one depicted in Figure 2, but clearly this is not what is observed in Figure 11. After some study, it was realized that there is a shock front in front of the projectile which precedes the arrival of the projectile at the gage location. Between the shock front and the

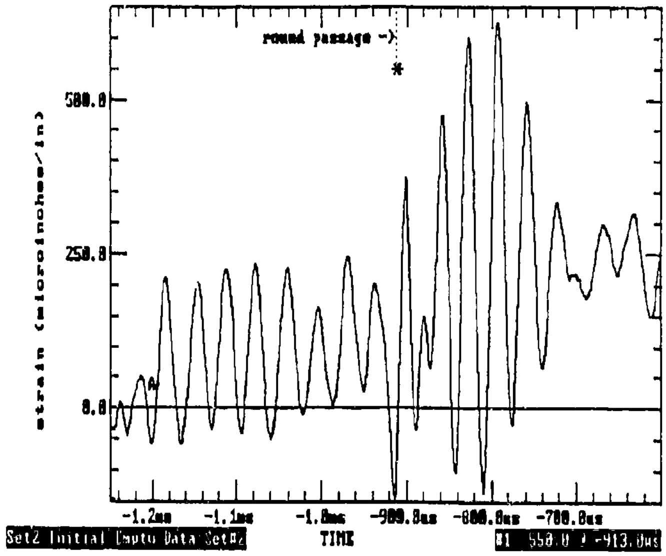


Figure 11. Figure 9 record - expanded time base.

projectile is a column of air with a pressure of about 25 atmospheres, roughly half the ballistic pressure at the rear face of the projectile. The shock front travels at a velocity which is roughly 26 percent greater than that of the projectile. The situation is depicted in **Figure 12**. This moving column of air led by the shock front creates the same strain pattern as a (fictitious) projectile travelling at a supercritical velocity. In a field cannon this strain pattern would be negligible compared with that caused by the moving ballistic pressure since the latter is an order of magnitude greater. In the 60-mm gun tube used in this study however, the magnitudes of the two pressures are comparable and create comparable dynamic strains in the tube. If steady-state theory applies, the strain pattern created by the moving shock should have the general appearance of Figure 3, a high frequency, short head wave travelling ahead of the shock front followed by a lower frequency, longer trailing wave travelling behind the shock front. Disregarding the Poisson contribution from the axial strain, the entire head wave and a portion of the trailing wave should dominate the strain history at the gage for a time prior to the arrival of the projectile. The projectile will bring with it a strain pattern resembling that of Figure 2. Thus, at some point in time between ignition and the arrival of the projectile, one should first observe the head wave which abruptly changes to the trailing wave as the shock front passes the gage. In Figure 11, point A

clearly shows the abrupt transition and establishment of the trailing wave. Its frequency is measured at 28.0 kHz, in good agreement with the theoretical prediction of 27.6 kHz. The head wave is not clearly evident, however. One possible reason for this is that the amplitude of the head wave for a velocity which is 25 percent supercritical, is only 13 percent that of the trailing wave. In addition, the theoretical frequency of this head wave is very high--90.65 kHz! Thus, the head wave could easily be buried in the 'noise' level of the strain signal because of its low amplitude and/or be difficult to detect because of the 1-mHz sampling rate used for the digitization of the signal.

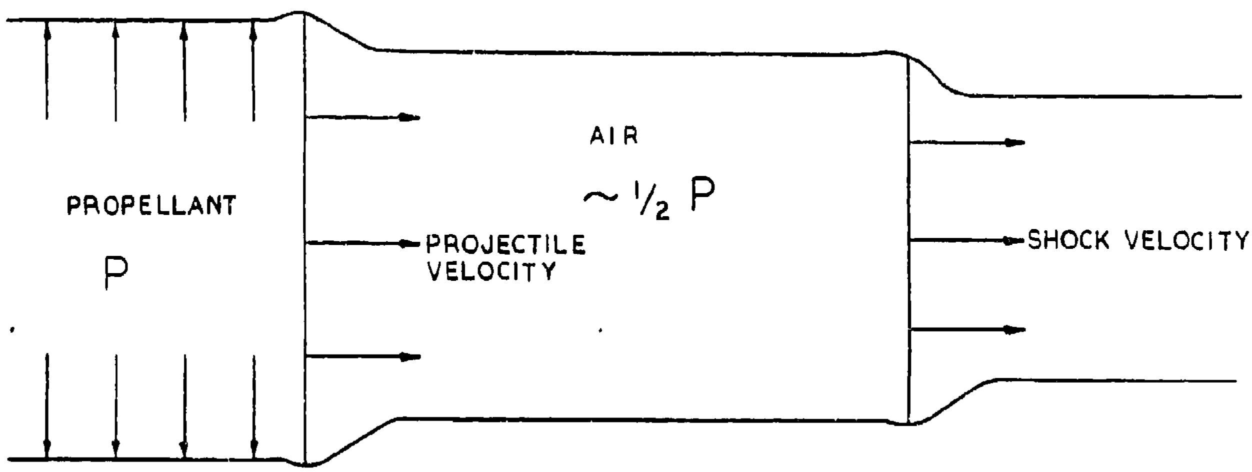


Figure 12. Schematic showing the ballistic pressure preceded by a faster moving shock.

Upon arrival of the projectile, the steady-state strain history is theoretically a linear combination of Figures 2 and 3. Figure 13 shows this superposition assuming that the pressure behind the shock front is half that behind the projectile and that the shock front arrives at the gage location 312 μs ahead of the projectile. Both assumptions represent approximate measured values from Figure 11. It can be seen that Figures 11 and 13 are in reasonable agreement.

EVIDENCE OF NONAXISYMMETRIC WAVES

The superposition of the classical solutions of Figures 2 and 3 give a reasonably good explanation of the appearance of the measured strains of Figure 9. It is apparent, however, that the replication is at best semi-quantitative, and differences exist at several locations throughout the record. Some of these can be attributed to the presence of nonaxisymmetric motions excluded by the classical theory thus far. Nonaxisymmetric vibrations (waves) are evident in a comparison of strain records from diametrically opposed strain gages. Figure 14 is a comparison from a firing subsequent to that of Figure 9. In this round, the evidence of nonaxisymmetric (beamlike) vibrations is particularly strong.

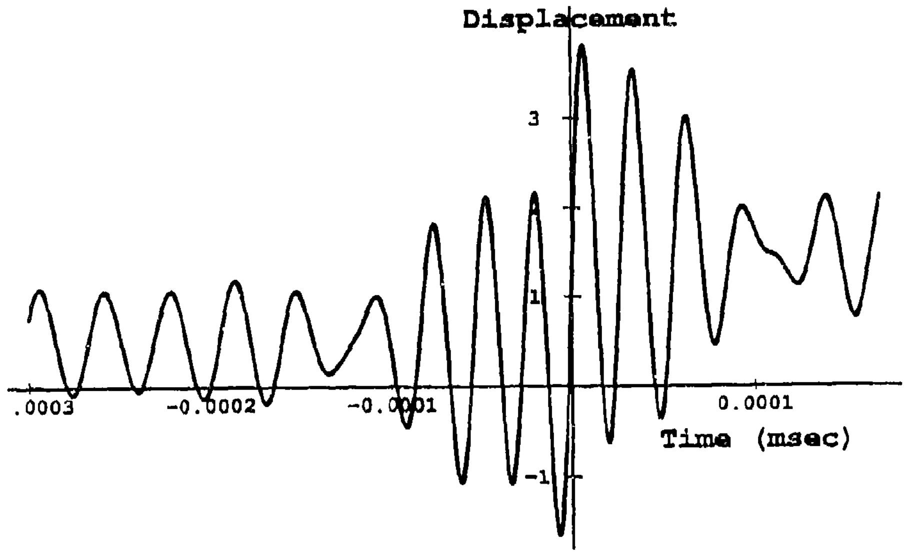


Figure 13. Theoretical superposition of steady-state displacements from Figures 2 and 3 compared with Figure 11.

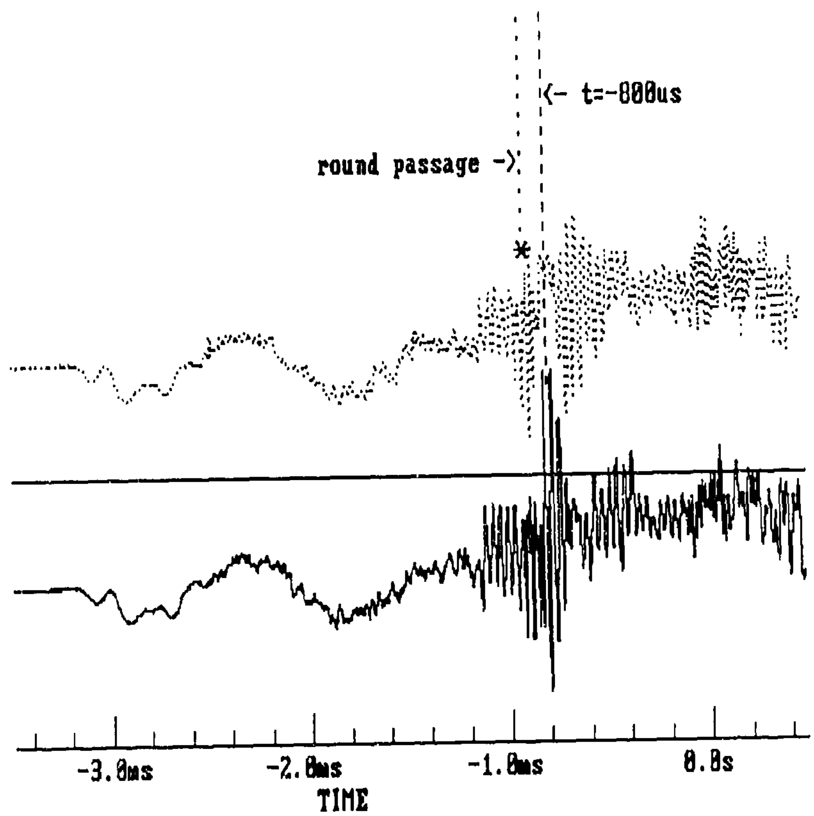


Figure 14. A comparison of diametrically opposed circumferential strain records 30 inches from muzzle, projectile velocity = 3905 ft/sec (round ID 38).

In Figure 14 we see that the strains on the diametrically opposed surfaces are in reasonable agreement. However, closer inspection reveals that there is a slight phase difference between the oscillatory motions of each side of the tube. By the time t = -800 μs, this phase difference is 180 degrees and causes a dramatic difference between the two diametrically opposed strains. Figure 15 shows these strains more clearly using an expanded time base. At t = -800 μs, the oscillations of the one surface maximize, while those of the opposite surface are practically nonexistent. It is believed that such a result can only be explained by the presence of beamlike vibrations in addition to the axisymmetric vibrations. This beamlike motion causes the tube wall beneath one gage to move radially outward, while that beneath the other moves radially inward. Quantitatively, if the magnitudes of the axisymmetric and beamlike modes are equal, there will be times when the sinusoidal components will add to twice the value on one side of the tube, while annihilating each other on the opposite side. This would explain Figure 15. In general, of course, beamlike motions and axisymmetric motions need not exist in equal amplitudes, and in other firings various amounts of each are evident. Thus, it is very probable that the strains induced by the passing projectile and shock front more generally consist of nonaxisymmetric as well as axisymmetric modes and that they interfere periodically in time. As previously mentioned, there must be some sort of coupling present to excite the nonaxisymmetric motions. No conclusions are drawn as to the nature of the coupling in this particular gun tube.

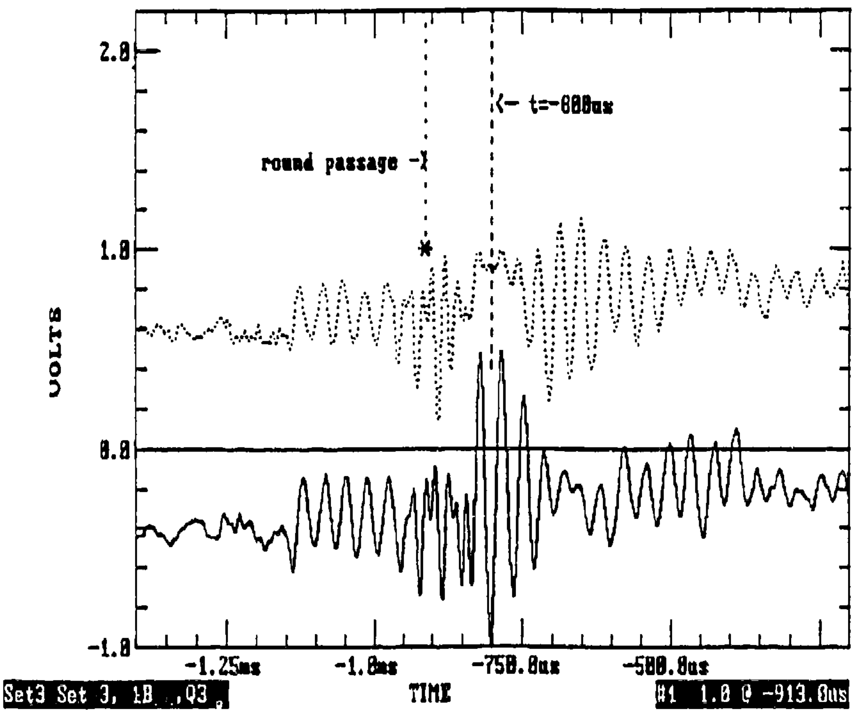


Figure 15. Figure 14 record--expanded time base.

HOW APPLICABLE ARE THE STEADY-STATE SOLUTIONS?

In all of the test firings of the 60-mm tube, the projectile enters the test section with a velocity close to critical, and the shock front enters with a velocity which is approximately 26 percent greater and therefore strongly supercritical. Under these conditions it was observed that the trailing wave associated with the shock front develops almost instantaneously and is plainly visible even at a location only six inches into the test section as shown in Figure 16. The development of the strain field associated with the motion of

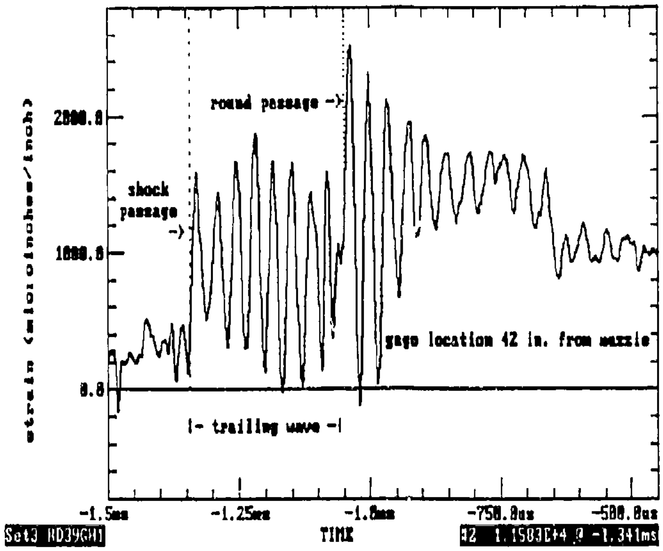


Figure 16. Circumferential strain record showing full development of wave trailing the shock front (round ID 39).

the projectile is not so easily assessed, however, owing to the interfering strains from the passage of the shock. To obtain a clearer picture, the shock front was eliminated by evacuating the tube via a vacuum pump prior to firing. This worked out very well and resulted in a sequence of strain records along the test section showing the development of the deformation caused by the moving ballistic pressure uncomplicated by the presence of the shock (Figures 17, 18, and 19). During this particular firing, the projectile has a slight acceleration through the test section so that its velocity changes from a subcritical 3860 ft/sec* to a supercritical 3984 ft/sec over a distance of two feet. (As previously mentioned, the theoretical critical velocity for axisymmetric

*Use of radar equipment to measure projectile velocity was not possible when the tube was evacuated because of the need for an expendable muzzle end cap to hold the vacuum. The velocities are average values estimated from the strain data.

deformation is 3924 ft/sec and for beamlike waves it is 3917 ft/sec.) **Figure 17** shows the tube strain at a position 42 inches from the muzzle--only 6 inches into the test section where the projectile velocity is estimated to be 3860 ft/sec. The strain record closely resembles that of Figure 2--the classic steady-state deformation from critical velocity theory. As the projectile passes the next strain gage, located 30 inches from the muzzle, its velocity is estimated to be extremely close to both critical values. The strain record from this location is shown in **Figure 18**. A loss of symmetry is apparent, there being greater wave development following passage of the projectile than there is prior to its passage. Evidently, the trailing wave associated with supercritical velocities has started to develop. **Figure 19** shows the strain at a location 18 inches from the muzzle where the velocity is estimated to be 3984 ft/sec. Further development of the trailing wave is evident. **Figure 20** shows Fourier spectra of the data of Figure 19 and reveals a dominant frequency following round passage to be 35.156 kHz. The theoretical frequency of axisymmetric trailing waves corresponding to a velocity of 3983 ft/sec is 33.313 kHz. Prior to round passage, the dominant Fourier component is 42.969 kHz corresponding to a theoretical 43.485 kHz for axisymmetric head waves at this velocity. Despite the close agreement in predicted and measured frequencies, a comparison of Figure 19 with Figure 3 shows that the development of the steady-state deformation at this slightly critical velocity is far from complete.

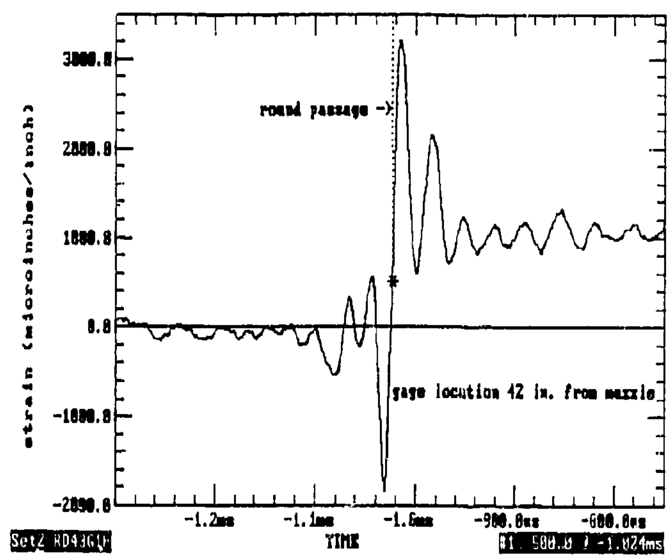


Figure 17. Circumferential strain record 42 inches from muzzle. Shock absent due to bore evacuation (round ID 43).

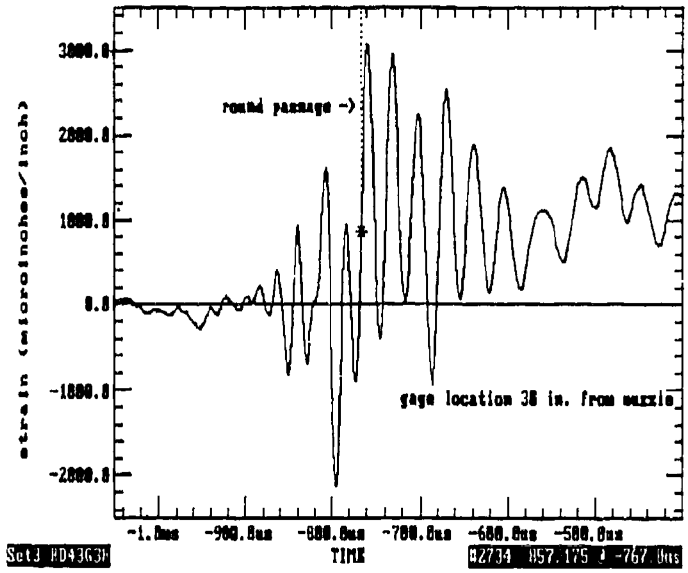


Figure 18. Circumferential strain record 30 inches from muzzle. Shock absent due to bore evacuation (round ID 43).

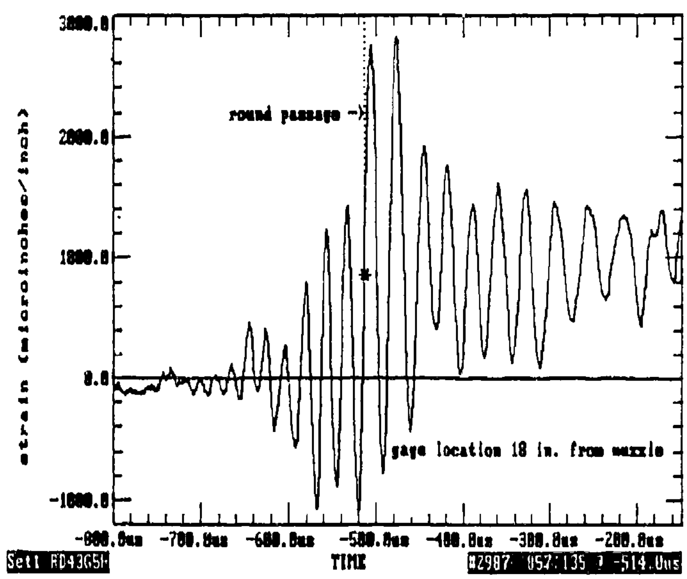


Figure 19. Circumferential strain record 18 inches from muzzle. Shock absent due to bore evacuation (round ID 43).

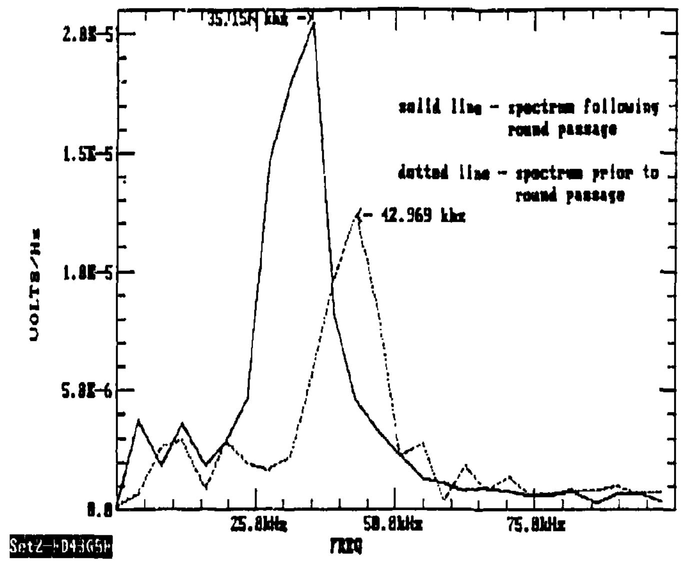


Figure 20. Fourier spectra of strain record of Figure 19 before and after round passage.

The evidence supplied by these test firings suggests that the steady-state deformation at subcritical projectile velocities (Figure 2) is established very rapidly. At velocities which are strongly supercritical (Figure 3), the development of a constant amplitude trailing wave is also very rapid. At velocities which are only slightly above critical, however, the development is much more gradual and may not even be established prior to projectile exit.

REFERENCES

1. T.E. Simkins, "Resonance of Flexural Waves in Gun Tubes," Proceedings of the Fifth U.S. Army Symposium on Gun Dynamics, ARCCB-SP-87023, 23-25 September 1987, Benet Laboratories, Watervliet, NY, pp. 64-77.

2. T.E. Simkins, "Wave Coupling and Resonance in Gun Tubes," Proceedings of the 59th Shock and Vibration Symposium, 18-20 October 1988, Albuquerque, NM; also ARCCB-TR-89008, Benet Laboratories, Watervliet, NY, March 1989.

3. T.E. Simkins, "Influence of Transient Flexural Waves on Dynamic Strains in Gun Tubes," ARCCB-TR-89020, Benet Laboratories, Watervliet, NY, August 1989.

4. S.P. Timoshenko and J.N. Goodier, Theory of Elasticity, Third Edition, McGraw-Hill, 1970, pp. 68-71.

5. P.P. Radkowski, J.I. Bluhm, and O.L. Bowie (Eds.), Thick-Walled Cylinder Handbook - Stresses and Strains in Elastic, Thick-Walled Circular Cylinders Resulting From Axially Symmetric Loadings," WAL No. 893/172, Watertown Arsenal, Watertown, NY, December 1954.

6. D.V. Shick and H.F. Tiersten, "A Variational Analysis of Resonance in Gun Tubes With Eccentric Bores," Proceedings of the Sixth U.S. Army Symposium on Gun Dynamics, ARCCB-SP-90015, 15-17 May 1990, Benet Laboratories, Watervliet, NY, pp. 175-198.

7. I. Mirsky and G. Herrmann, "Axially Symmetric Motions of Thick Cylindrical Shells," Journal of Applied Mechanics, Vol. 25, March 1958, pp. 97-102.

8. H. Reismann, "Response of a Prestressed Cylindrical Shell to Moving Pressure Load, Developments in Mechanics," in: Solid Mechanics - Proceedings of the Eighth Midwestern Mechanics Conference, Pergamon Press, Part II, Vol. 2, 1965, pp. 349-363.

TECHNICAL REPORT INTERNAL DISTRIBUTION LIST

	NO. OF COPIES
CHIEF, DEVELOPMENT ENGINEERING DIVISION	
ATTN: SMCAR-CCB-DA	1
-DC	1
-DI	1
-DR	1
-DS (SYSTEMS)	1
CHIEF, ENGINEERING SUPPORT DIVISION	
ATTN: SMCAR-CCB-S	1
-SD	1
-SE	1
CHIEF, RESEARCH DIVISION	
ATTN: SMCAR-CCB-R	2
-RA	1
-RE	1
-RM	1
-RP	1
-RT	1
TECHNICAL LIBRARY ATTN: SMCAR-CCB-TL	5
TECHNICAL PUBLICATIONS & EDITING SECTION ATTN: SMCAR-CCB-TL	3
OPERATIONS DIRECTORATE ATTN: SMCWV-ODP-P	1
DIRECTOR, PROCUREMENT DIRECTORATE ATTN: SMCWV-PP	1
DIRECTOR, PRODUCT ASSURANCE DIRECTORATE ATTN: SMCWV-QA	1

NOTE: PLEASE NOTIFY DIRECTOR, BENET LABORATORIES, ATTN: SMCAR-CCB-TL, OF ANY ADDRESS CHANGES.

TECHNICAL REPORT EXTERNAL DISTRIBUTION LIST

	NO. OF COPIES
ASST SEC OF THE ARMY RESEARCH AND DEVELOPMENT ATTN: DEPT FOR SCI AND TECH THE PENTAGON WASHINGTON, D.C. 20310-0103	1
ADMINISTRATOR DEFENSE TECHNICAL INFO CENTER ATTN: DTIC-FDAC CAMERON STATION ALEXANDRIA, VA 22304-6145	12
COMMANDER US ARMY ARDEC	
ATTN: SMCAR-AEE	1
SMCAR-AES, BLDG. 321	1
SMCAR-AET-O, BLDG. 351N	1
SMCAR-CC	1
SMCAR-CCP-A	1
SMCAR-FSA	1
SMCAR-FSM-E	1
SMCAR-FSS-D, BLDG. 94	1
SMCAR-IMI-I (STINFO) BLDG. 59	2
PICATINNY ARSENAL, NJ 07806-5000	
DIRECTOR US ARMY BALLISTIC RESEARCH LABORATORY ATTN: SLCBR-DD-T, BLDG. 305 ABERDEEN PROVING GROUND, MD 21005-5066	1
DIRECTOR US ARMY MATERIEL SYSTEMS ANALYSIS ACTV ATTN: AMXSY-MP ABERDEEN PROVING GROUND, MD 21005-5071	1
COMMANDER HQ, AMCCOM ATTN: AMSMC-IMP-L ROCK ISLAND, IL 61299-6000	1
COMMANDER ROCK ISLAND ARSENAL ATTN: SMCRI-ENM ROCK ISLAND, IL 61299-5000	1
DIRECTOR US ARMY INDUSTRIAL BASE ENGR ACTV ATTN: AMXIB-P ROCK ISLAND, IL 61299-7260	1
COMMANDER US ARMY TANK-AUTMV R&D COMMAND ATTN: AMSTA-DDL (TECH LIB) WARREN, MI 48397-5000	1
COMMANDER US MILITARY ACADEMY ATTN: DEPARTMENT OF MECHANICS WEST POINT, NY 10996-1792	1
US ARMY MISSILE COMMAND REDSTONE SCIENTIFIC INFO CTR ATTN: DOCUMENTS SECT, BLDG. 4484 REDSTONE ARSENAL, AL 35898-5241	2
COMMANDER US ARMY FGN SCIENCE AND TECH CTR ATTN: DRXST-SD 220 7TH STREET, N.E. CHARLOTTESVILLE, VA 22901	1
COMMANDER US ARMY LABCOM MATERIALS TECHNOLOGY LAB ATTN: SLCMT-IML (TECH LIB) WATERTOWN, MA 02172-0001	2

NOTE: PLEASE NOTIFY COMMANDER, ARMAMENT RESEARCH, DEVELOPMENT, AND ENGINEERING CENTER, US ARMY AMCCOM, ATTN: BENET LABORATORIES, SMCAR-CCB-TL, WATERVLIET, NY 12189-4050, OF ANY ADDRESS CHANGES.

TECHNICAL REPORT EXTERNAL DISTRIBUTION LIST (CONT'D)

	NO. OF COPIES
COMMANDER US ARMY LABCOM, ISA ATTN: SLCIS-IM-TL 2800 POWDER MILL ROAD ADELPHI, MD 20783-1145	1
COMMANDER US ARMY RESEARCH OFFICE ATTN: CHIEF, IPO P.O. BOX 12211 RESEARCH TRIANGLE PARK, NC 27709-2211	1
DIRECTOR US NAVAL RESEARCH LAB ATTN: MATERIALS SCI & TECH DIVISION CODE 26-27 (DOC LIB) WASHINGTON, D.C. 20375	1 1
DIRECTOR US ARMY BALLISTIC RESEARCH LABORATORY ATTN: SLCBR-IB-M (DR. BRUCE BURNS) ABERDEEN PROVING GROUND, MD 21005-5066	1
COMMANDER AIR FORCE ARMAMENT LABORATORY ATTN: AFATL/MN EGLIN AFB, FL 32542-5434	1
COMMANDER AIR FORCE ARMAMENT LABORATORY ATTN: AFATL/MNF EGLIN AFB, FL 32542-5434	1
MIAC/CINDAS PURDUE UNIVERSITY 2595 YEAGER ROAD WEST LAFAYETTE, IN 47905	1

NOTE: PLEASE NOTIFY COMMANDER, ARMAMENT RESEARCH, DEVELOPMENT, AND ENGINEERING CENTER, US ARMY AMCCOM, ATTN: BENET LABORATORIES, SMCAR-CCB-TL, WATERVLIET, NY 12189-4050, OF ANY ADDRESS CHANGES.